

PYCNONUCLEAR BURNING AND ACCRETING NEUTRON STARS

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We outline the phenomenon of deep crustal heating in transiently accreting neutron stars. It is produced by nuclear transformations (mostly, by pycnonuclear reactions) in accreted matter while this matter sinks to densities $\rho \gtrsim 10^{10} \text{ g cm}^{-3}$ under the weight of freshly accreted material. We consider then thermal states of transiently accreting neutron stars (with mean mass accretion rates $\dot{M} \sim 10^{-14} - 10^{-9} \text{ M}_{\odot}/\text{yr}$) determined by deep crustal heating. In a simplified fashion we study how the thermal flux emergent from such stars depends on the properties of superdense matter in stellar interiors. We analyze the most important regulators of the thermal flux: strong superfluidity in the cores of low-mass stars and fast neutrino emission (in nucleon, pion-condensed, kaon-condensed, or quark phases of dense matter) in the cores of high-mass stars. We compare the results with observations of soft X-ray transients in quiescent states.

1 Introduction

Nuclear burning of matter is the keystone of stellar physics. It is vitally important for main-sequence stars where it proceeds in *thermonuclear* regime. In this regime, Coulomb barrier in nuclear reactions is penetrated owing to the thermal energy of colliding nuclei.

In the present paper, we discuss another, *pycnonuclear* regime of nuclear burning. Coulomb barrier in pycnonuclear reactions is penetrated due to (quantum) zero-point motion of the reacting nuclei. While the thermonuclear regime is realized in sufficiently low-density and warm plasma (centers of main-sequence stars as an example), the pycnonuclear regime operates at high densities and not too high temperatures. The pycnonuclear reaction rates are almost temperature independent, i.e., this burning occurs even at $T = 0$. The formalism of nuclear reactions in the pycnonuclear regime, as well as in the intermediate thermo-pycnonuclear regimes, was developed in a seminal paper by Salpeter & van Horn [1]. The pycnonuclear reactions have been considered later in a number of publications (e.g., [2, 3] and references therein).

We analyse implication of the concept of pycnonuclear burning to the physics of neutron stars (NSs). They are compact stellar objects of mass

$M \sim 1.4 M_{\odot}$ (M_{\odot} being the solar mass) and radius $R \sim 10$ km. The density of matter in their cores reaches $\sim 10^{15}$ g cm $^{-3}$ (i.e., several times nuclear matter density). The composition and equation of state of the NS cores cannot be unambiguously calculated and is still almost not constrained by observations (see, e.g., Ref. [4]). For instance, inner NS cores may contain nucleon matter, pion- or kaon condensates, or quark matter. Neither of this hypothesis can be accepted or rejected at present. Neutrons, protons, and other strongly interacting species can be in superfluid state. Microscopic calculations predict density dependent critical temperatures of these superfluids in the range $10^8 - 10^{10}$ K or higher (e.g., [5, 6] and references therein). Such calculations are very model dependent and introduce additional uncertainty into the physics of NS interiors.

The internal structure of NSs is studied by confronting theoretical models with observations in many ways, for instance, basing on precisely measured masses of some radio pulsars in binary systems (e.g., [7, 4]), or comparing the theory and observations of cooling NSs (e.g., [8, 9, 10]). Pycnonuclear burning of matter in transiently accreting NSs gives another method to study the internal structure of NSs as described below.

2 Pycnonuclear burning and deep crustal heating

Let us follow the evolution of accreted matter in a transiently accreting NS (in a binary system). An infall of accreted matter is accompanied by a large energy release (~ 300 MeV per accreting nucleon) due to the transformation of infall energy into heat. This heat is most likely radiated away by photons from the NS surface and cannot warm up the star. An accreted material sinks then gradually into the NS interior under the weight of newly infalling matter. In the outer stellar layer (at densities $\rho \lesssim 10^{10}$ g cm $^{-3}$, a few tens of meters under the surface) this matter burns (mainly in the thermonuclear regime, in a steady or explosive manner) into heavier elements, to Fe. The energy released in this burning is mostly transferred by thermal conductivity to the surface and again radiated away by photons, producing no heating of NS interiors.

Let us focus on subsequent transformations of accreted matter at $10^{10} \lesssim \rho \lesssim 10^{13}$ g cm $^{-3}$. They include: beta captures, absorption and emission of neutrons, and pycnonuclear reactions. These transformations and associated energy release have been considered in detail by Haensel & Zdunik [11] (see the monograph [12] for references to some earlier work). The appropriate reaction rates do not depend on temperature but strongly depend on ρ . It is sufficient

to assume that any transformation occurs in a certain infinitesimally thin NS layer. The main energy release (0.79 MeV per accreting baryon) takes place [11] at densities from about 10^{12} to 10^{13} g cm $^{-3}$, about 1 km under the surface, in three pycnonuclear reactions. The total energy release is about 1.45 MeV per accreting baryon. The total heating power is determined by the mass accretion rate \dot{M} and estimated as

$$L_{\text{dh}} = 1.45 \text{ MeV } \dot{M}/m_{\text{N}} \approx 8.74 \times 10^{33} \dot{M}/(10^{-10} \text{ M}_{\odot} \text{ yr}^{-1}) \text{ erg s}^{-1}, \quad (1)$$

where m_{N} is the nucleon mass. This energy release produces *deep crustal heating* of accreted matter. In contrast to (much stronger) heating near the surface, this heat is spread by thermal conductivity over the entire NS and warms it up.

3 Soft X-ray transients

It is likely that deep crustal heating manifests itself in soft X-ray transients (SXRTs). We mean SXRTs containing NSs in binary systems with low-mass companions (low-mass X-ray binaries) [13]. Such objects undergo the periods of outburst activity (days–months, sometimes years) superimposed with the periods of quiescence (months–decades). This transient activity is most probably regulated by accretion from disks surrounding the NSs. An active period is associated with a switched-on accretion. The accretion energy released at the NS surface is large for a transient to look like a bright X-ray source with the luminosity $L_X \sim 10^{36} - 10^{38}$ erg s $^{-1}$. The accretion is switched off or strongly suppressed during quiescence periods when L_X drops to $L_X \lesssim 10^{34}$ erg s $^{-1}$.

The nature of the quiescent emission is still uncertain. The hypothesis that this emission is produced by the thermal flux emergent from the NS interior has been rejected initially due to two reasons. First, the radiation spectra fitted with the blackbody model have given unreasonably small NS radii. Second, the NSs in SXRTs have been expected to be old and thus internally cold; their quiescent emission should have been much lower than the observed one. These arguments were questioned by Brown et al. [14] who suggested that the NSs can be warmed up by the deep crustal heating while the radiation spectra can be fitted with the hydrogen atmosphere models yielding realistic NS radii. Since the emergent radiation flux may depend on the NS internal structure this opens an attractive possibility (see [15, 16, 17, 18] and references therein) to explore the internal structure by comparing observations of SXRTs in quiescence with theoretical models.

4 Thermal states of accreting neutron stars

Let us outline the theory of thermal states of transiently accreting NSs. Following [10] we will make a general but not very accurate analysis of the problem. The NSs of study will have internal temperatures $T \lesssim 3 \times 10^8$ K. They are thermally inertial objects with thermal relaxation times $\sim 10^4$ yr [16]. The quiescence intervals in SXRTs are much shorter than these relaxation times. We neglect short-term variability in the stellar crust; it can be associated [15, 18] with variable residual accretion in quiescence, thermal relaxation of transient deep crustal heating, etc. Instead, we focus on a (quasi)stationary steady state of the NS determined by the accretion rate $\dot{M} \equiv \langle \dot{M} \rangle$ (from 10^{-14} to 10^{-9} M_\odot/yr) averaged over time intervals comparable with the thermal relaxation time. Thus we replace variable \dot{M} with $\langle \dot{M} \rangle$. The accretion rates of study are too low to noticeably increase NS mass, M , during long periods of SXRT evolution.

Thermal states of accreting NSs can be found by solving the equation of thermal balance [19] in the approximation of thermally relaxed, isothermal stellar interior enclosed by a thin ($\rho \lesssim 10^{10}$ g cm $^{-3}$) heat-blanketing envelope:

$$C(T_i) \frac{dT_i}{dt} = L_{\text{dh}}^\infty(\dot{M}) - L_\nu^\infty(T_i) - L_\gamma^\infty(T_s). \quad (2)$$

Here, T_s is the effective surface temperature, $T_i(t)$ is the internal temperature (constant throughout the isothermal interior), C is the NS total heat capacity, L_ν^∞ is the neutrino luminosity, L_γ^∞ the photon luminosity, and L_{dh}^∞ is the deep-heating power. The relation between T_i and T_s is determined (e.g., [20]) from the solution of thermal conduction problem in the heat-blanketing envelope. Equation (2) takes proper account of the effects of General Relativity (see Ref. [21], for details) important in such compact objects as NSs. Particularly, T_s refers to a local reference frame on the NS surface while the effective temperature detected by a distant observer is $T_s^\infty = T_s \sqrt{1 - r_g/R}$, where $r_g = 2GM/c^2$ is the Schwarzschild radius, M the gravitational NS mass, R the circumferential NS radius, and G is the gravitational constant. The internal temperature T_i in Eq. (2) also refers to a distant observer, while the local internal temperature is $T(r, t) = T_i(t) e^{-\Phi(r)}$, $\Phi(r)$ being the metric function, with $e^{\Phi(R)} = \sqrt{1 - r_g/R}$. The quantities C and L_α^∞ ($\alpha = \nu, \gamma, \text{dh}$) have to be calculated with account for General Relativity; all three quantities L_α^∞ refer to a distant observer. In particular, $L_\gamma^\infty = 4\pi R^2 \sigma T_s^4 (1 - r_g/R)$, and $L_\nu^\infty = \int dV Q_\nu e^{2\Phi}$, where Q_ν is the neutrino emissivity and dV is a proper volume element. A steady-state accretion in General Relativity is characterized

by a constant mass accretion rate \dot{M} which determines [22] constant number of accreting baryons passing through a sphere of any radial coordinate r per unit time for a distant observer. For a deep crustal heating in a relatively thin NS envelope one approximately has (e.g., Ref. [23]) $L_{\text{dh}}^\infty = L_{\text{dh}} \sqrt{1 - r_g/R}$, where L_{dh} is given by Eq. (1). Since \dot{M} in SXRTs is determined with large uncertainties, we set $L_{\text{dh}}^\infty = L_{\text{dh}}$ in our subsequent analysis.

As discussed above, we are interested in the steady-state solution of Eq. (2). In this case it is sufficient to solve the simplified heat-balance equation

$$L_{\text{dh}}^\infty(\dot{M}) = L_\nu^\infty(T_i) + L_\gamma^\infty(T_s), \quad (3)$$

where L_{dh}^∞ is known once \dot{M} is specified. The solutions give us a *heating curve*, the dependence of the photon luminosity on the mean accretion rate, $L_\gamma^\infty(\dot{M})$. It has been shown (e.g., Ref. [23]) that the theory of heating of accreting NSs is very similar to theory of cooling of isolated NSs.

To solve Eq. (3) we employ a simple toy model [10] of the NS thermal structure. It allows us to analyze various neutrino emission scenarios in NS cores. Let us remind the main points.

The toy model assumes that a NS core is divided into three zones: the *outer* zone, $\rho < \rho_s$; the *transition* zone, $\rho_s \leq \rho < \rho_f$; and the *inner* zone, $\rho \geq \rho_f$. If the NS central density $\rho_c \leq \rho_s$, two last zones are absent.

In the outer zone, the neutrino emission is supposed to be *slow*, while in the inner zone it is *fast*. The neutrino emissivity is assumed to be given by:

$$Q_\nu^{\text{slow}}(\rho \leq \rho_s) = Q_s T_9^8, \quad Q_\nu^{\text{fast}}(\rho \geq \rho_f) = Q_f T_9^6. \quad (4)$$

Here, T_9 is the local internal stellar temperature T in 10^9 K, while Q_s and Q_f are constants. For simplicity, the toy model uses the linear interpolation in ρ between Q_ν^{slow} and Q_ν^{fast} in the transition zone.

This *generic* description of Q_ν covers many *physical* models of nucleon and exotic supranuclear matter with different leading neutrino processes listed in Tables 1 and 2 (from Ref. [10]). In these tables, N is a nucleon (neutron or proton, n or p); e is an electron; ν and $\bar{\nu}$ are neutrino and antineutrino; q is a quasinucleon (mixed n and p states); u and d are quarks.

Slow neutrino processes are important in the outer NS cores composed of nucleons and electrons where the proton fraction is too low to allow for fast direct Urca (Durca) process [24]. In particular, Q_s can describe modified Urca (Murca) process in nonsuperfluid nucleon matter, or weaker NN-bremsstrahlung (e.g., nn-bremsstrahlung if Murca is suppressed by a strong proton superfluidity as considered in Ref. [25]).

Table 1: Main processes of slow neutrino emission in nucleon matter: Murca and bremsstrahlung (brems)

Process			$Q_s, \text{ erg cm}^{-3} \text{ s}^{-1}$
Murca	$nN \rightarrow pNe\bar{\nu}$	$pNe \rightarrow nN\nu$	$10^{20} - 3 \times 10^{21}$
Brems.	$NN \rightarrow NN\nu\bar{\nu}$		$10^{19} - 10^{20}$

Table 2: Leading processes of fast neutrino emission in nucleon matter and three models of exotic matter

Model	Process		$Q_f, \text{ erg cm}^{-3} \text{ s}^{-1}$
Nucleon matter	$n \rightarrow pe\bar{\nu}$	$pe \rightarrow n\nu$	$10^{26} - 10^{27}$
Pion condensate	$q \rightarrow qe\bar{\nu}$	$qe \rightarrow q\nu$	$10^{23} - 10^{26}$
Kaon condensate	$q \rightarrow qe\bar{\nu}$	$qe \rightarrow q\nu$	$10^{23} - 10^{24}$
Quark matter	$d \rightarrow ue\bar{\nu}$	$ue \rightarrow d\nu$	$10^{23} - 10^{24}$

Fast neutrino emission is produced in the inner NS cores. Its intensity is regulated by the parameter Q_f and depends on the composition of dense matter. The fast emission may be produced either by a very powerful Durca process in nucleon matter or somewhat weaker similar processes in exotic phases of matter (pion condensed, kaon condensed, or quark matter) [26, 27]. The bottom line of Table 2 refers to nonsuperfluid quark matter in NS cores.

The toy model solves Eq. (3) under a number of simplified assumptions [10]. The density profile in the star is approximate, $\rho(r) = \rho_c (1 - r^2/R^2)$, so that the NS mass is $M = 8\pi R^3 \rho_c / 15$. The effect of various equations of state can be mimicked by choosing different $M - R$ relations. For simplicity, following Ref. [10], we set $R = 12$ km and allow the central density ρ_c to vary from 7×10^{14} to $1.4 \times 10^{15} \text{ g cm}^{-3}$, varying thus M from $1.02 M_\odot$ to $2.04 M_\odot$. More realistic $M - R$ relations will not change our principal conclusions.

5 Results and discussion

The resulting heating curves are presented in Fig. 1. For certainty, we consider two representative NS models: a low-mass model ($\rho_c = 8 \times 10^{14} \text{ g cm}^{-3}$,

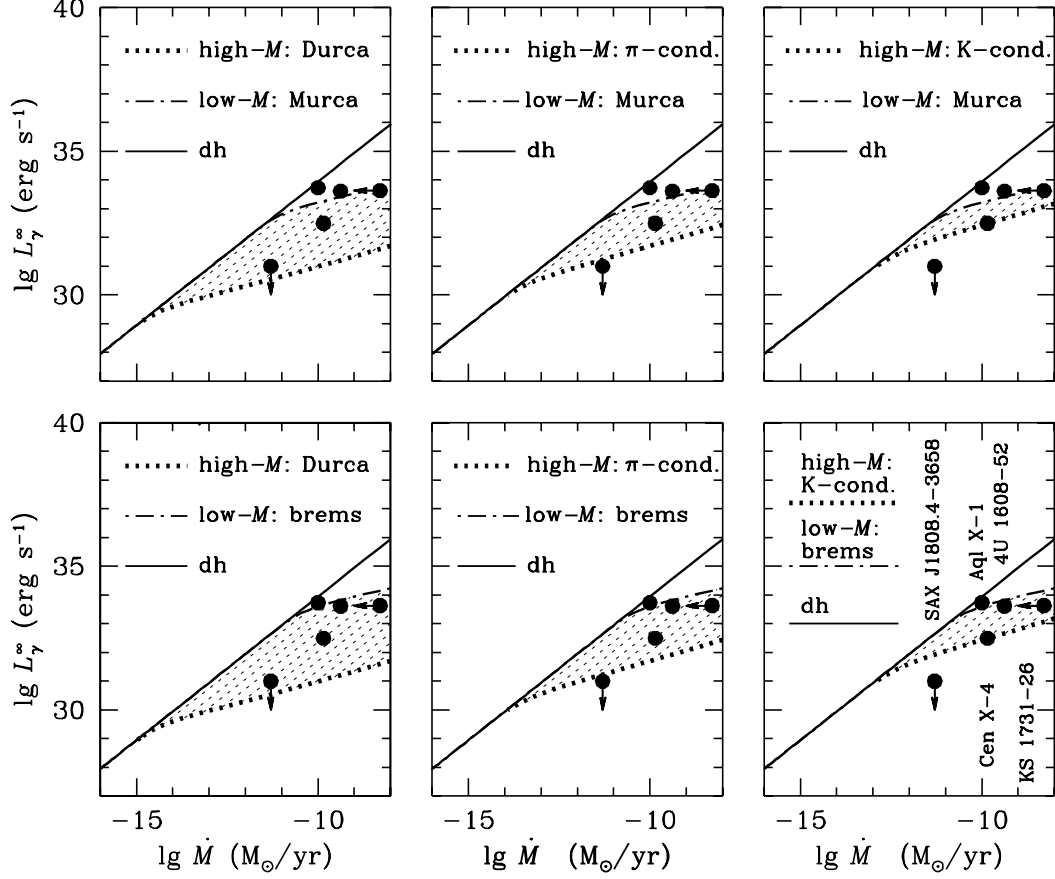


Figure 1: Allowable thermal states (dotted regions) of accreting NSs for six physical pictures of NS interiors compared with observations of SXRTs.

$M = 1.16 M_\odot$) and a high-mass model ($\rho_c = 1.4 \times 10^{15} \text{ g cm}^{-3}$, $M = 2.04 M_\odot$) and adopt $\rho_s = 8 \times 10^{14} \text{ g cm}^{-3}$ and $\rho_f = 10^{15} \text{ g cm}^{-3}$. Thus the low-mass NS model contains the outer core alone and is a typical example of a NS with slow neutrino emission. The high-mass model contains a bulky inner core and is an example of a NS governed by fast neutrino emission.

Let us fix a *physical picture* of NS interiors (a set of four parameters, Q_s , Q_f , ρ_s , and ρ_f , in our case). It has to be the same for all NSs, and we would like to constrain it from observations of SXRTs. Figure 1 shows six representative cases. Solid curves present the deep heating power, L_{dh}^∞ , which is the absolute upper limit of L_γ^∞ (see Eq. (3)). The heating curves of low-mass NSs are shown by dash-and-dot lines and the curves of high-mass NSs are shown by dotted lines. Three upper panels display low-mass NSs

with slow neutrino emission determined by Murca process in nonsuperfluid NS cores ($Q_s = 10^{21}$). Three lower panels display low-mass stars with very slow neutrino emission appropriate to neutron-neutron bremsstrahlung in the NS cores with strong proton superfluidity ($Q_s = 3 \times 10^{19}$). The superfluidity damps Murca process and enables us to obtain hotter NSs, just as in the theory of cooling NSs [25, 9]. Two left panels exhibit high-mass NSs with the fastest neutrino emission from nucleon NS cores with open Durca process ($Q_f = 10^{27}$). Two middle panels show high-mass NSs with pion-condensed inner cores ($Q_f = 10^{25}$), while two right panels show high-mass NSs with kaon-condensed or quark cores ($Q_f = 10^{23}$).

A heating curve of a low-mass NS (with given Q_s) provides an upper limit of L_γ^∞ , whereas a heating curve of a high-mass NS (with given Q_f) gives a lower limit of L_γ^∞ , for a fixed physical picture of NS interiors. Varying the NS mass from the lower values to the higher we obtain a family of heating curves which fill in the (dotted) space between the upper and lower curves. A group of NSs whose heating curves lie essentially between the upper and lower curves will be called *medium-mass* stars. Their mass range is sensitive to the position and width of the transition layer ($\rho_s \lesssim \rho \lesssim \rho_f$) between the slow and fast neutrino emission zones, in full analogy with the theory of cooling NSs [25, 9, 10].

As seen from Fig. 1 and Eq. (3), there are two limiting regimes.

Photon emission regime is realized in cold enough NSs, where \dot{M} is rather low and $L_\nu^\infty \ll L_\gamma^\infty$. It is equivalent to the photon emission stage of cooling NSs. In this case Eq. (3) reduces to: $L_{\text{dh}}^\infty(\dot{M}) = L_\gamma^\infty(T_s)$, i.e., all the heat released in the deep crust diffuses to the surface and is emitted away by photons. Accordingly, the photon luminosity is determined by the mass accretion rate and is independent of the NS internal structure.

Neutrino emission regime is realized in warmer NSs, where \dot{M} is sufficiently high and $L_\nu^\infty \gg L_\gamma^\infty$, i.e., the deep crustal heat is spread by thermal diffusion over the star and carried away by neutrino emission. This regime is equivalent to neutrino stage in cooling NSs. The thermal balance equation then reads: $L_{\text{dh}}^\infty(\dot{M}) = L_\nu^\infty(T_i)$, which gives T_i . The surface photon luminosity just responds to T_i and depends on the NS internal structure.

Analytic estimates of T_s in both regimes are given in Ref. [23]. As seen from Fig. 1, a transition from the photon to neutrino regime with increasing \dot{M} takes place at $\dot{M} \sim 10^{-15}$, 10^{-14} , and $10^{-13} \text{ M}_\odot/\text{yr}$, for high-mass NS models with nucleon Durca, pion-condensed, and kaon-condensed inner cores, respectively.

Thus, for any physical picture of NS interiors we obtain its own upper and lower heating curves, and intermediate heating curves of medium-mass NSs. These results can be confronted with observations of SXRTs containing NSs. Figure 1 presents an example of such an analysis for five SXRTs. Following Ref. [23] we take the observational data for Aql X-1, Cen X-4, 4U 1608-522, KS 1731-26, and SAX J1808.4-3658 from Refs. [28, 29], [30, 13], [31, 13], [32, 17], and [33, 34], respectively. We regard L_γ^∞ as the thermal surface luminosity of these sources in quiescent states, and we regard \dot{M} as the mass accretion rate averaged [23] over representative intervals of time. These time intervals include quiescent and active periods (while the accreted mass is mainly accumulated in the active states). The value of \dot{M} for KS 1731-26 is most probably an upper limit. No quiescent thermal emission has been detected from SAX J1808.4-3658, and we present the upper limit of L_γ^∞ for this source (see [23] for details). The data are rather uncertain. Thus we plot the observational points as thick dots.

If the interpretation of quiescent emission as the thermal emission from the NS surfaces is correct, then all five NSs are heated to the neutrino emission regime ($L_{\text{dh}}^\infty \gg L_\gamma^\infty$). Since L_{dh}^∞ is reliably determined, for a known \dot{M} , and L_γ^∞ is measured, one can immediately estimate the neutrino luminosity of each source from Eq. (3): $L_\nu^\infty = L_{\text{dh}}^\infty - L_\gamma^\infty$. In all our cases L_ν^∞ is comparable with L_{dh}^∞ (Fig. 1).

As seen from Fig. 1, we can treat NSs in 4U 1608-52 and Aql X-1 as low-mass NSs with very weak neutrino emission from their cores. NSs in Cen X-4 and SAX J1808.4-3658 seem to require the enhanced neutrino emission and are thus more massive. The status of NS in KS 1731-26 is less certain [23] because of poorly determined \dot{M} . If the real value of \dot{M} is close to the assumed one, it may also require some enhanced neutrino emission. Similar conclusions have been made, particularly, in Refs. [15, 16, 30, 17, 28, 18, 32] with respect to some of these sources or selected groups.

Let us disregard the SAX source for a moment. We see that the observational point for Cen X-4 lies above (or near) all three limiting heating curves for massive NSs (with kaon- or pion condensate, and nucleon Durca cores). Accordingly, we can treat the NS in Cen X-4 either as high-mass NS (with kaon-condensed or quark core) or as medium-mass NS (with pion-condensed, quark, or Durca-allowed nucleon core). If further observations confirm the current status of SAX J1808.4-3658, then we will have the only choice to treat this NS as a high-mass NS with the nucleon core (and the NS in Cen X-4 as medium-mass NS with the nucleon core). This would disfavor the hypothesis

on exotic phases of matter in NS cores.

Our generic description of neutrino emission (Sect. 4) is too flexible to fix the position of the transition layer in the NS cores where a slow emission transforms into a fast one. Adopting a specific physical picture of NS interiors, with this position determined by microphysics input, we would be able to construct the sequences of heating curves for NSs with different M , and attribute certain values of M to any source (“weigh” NSs in SXRTs, as proposed by Colpi et al. [16], just as in the case of cooling isolated NSs [25, 9]).

The assumption that the observed X-ray emission of SXRTs in quiescence emerges from NS interior is still an attractive hypothesis. However, the theory of deep crustal heating is solid. This phenomenon, produced mainly by pycnonuclear reactions in the inner NS crusts, should occur in accreting NSs leading to observational consequences.

Because of the similarity between the heating and cooling theories, the observations of cooling isolated NSs and NSs in SXRTs can be analyzed together increasing statistics of the sources and confidence of the results. Recently the theory of cooling NSs has been confronted with observations in Refs. [10, 25, 9]. Some cooling NSs (first of all, RX J0822–43, and PSR 1055–52) can be interpreted as low-mass NSs with strong proton superfluidity in their cores. Other sources (first of all, Vela, Geminga, and RX J0205+6449) seem to require enhanced neutrino emission but the nature of this emission is uncertain, just as for SXRTs disregarding SAX J808.4–3658. In this context, the latter source is now the only one which disfavors exotic phases of matter in the NS cores.

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